Temperature dependence of magnetoresistance effect in $\text{Ag-Fe}_3\text{O}_4$ composites films

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Abstract

We have observed an anomalous magnetoresistance effect in $\text{Ag}_x\text{-(Fe}_3\text{O}_4)_{1-x}$ composite films. A positive MR value is found at small values of x . As the temperature is decreased, the positive MR ratio becomes significantly larger and appears with a wider range of x . The thermal influence on magneto-transport behavior in $\text{Ag}_x\text{-(Fe}_3\text{O}_4)_{1-x}$ composite films confirms that the spin injection from Fe_3O_4 into Ag granules induces spin accumulation in Ag granules and thus impedes the current causing a larger resistance under a field.

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Spintronics, in which use is made of the electron spin degree of freedom, has been investigated extensively in the past few years with many intriguing topics having been studied [1]. One of the key issues is the spin injection and the associated spin accumulation. About 15 years ago Johnson and Silsbee proposed the following idea that electrical charges with polarized spins injected from a ferromagnetic slab into a thin paramagnetic bar carry current with spins and thus induce a spin accumulation near the interface [2]. A second ferromagnetic stripe contacting with the non-magnetic thin layer on the other side acts as a spin analyzer. In general, electrical current driven across a ferromagnetic–nonmagnetic metal interface would be spin polarized so that the spin-polarized electrons would penetrate into the nonmagnetic metal for a length characterized by the spin diffusion length δ_s . Compared those observed in a ferromagnetic–nonmagnetic–ferromagnetic trilayer, we have demonstrated previously that the above phenomenon can also be detected in

ferromagnetic/nonmagnetic metal composite systems consisting of nano-scaled metal granules randomly dispersed in the magnetic Fe_3O_4 matrix. Furthermore, the spin diffusion length δ_s in metal at room temperature can be evaluated [3,4].

The preparation as well as characterization of $\text{Ag}_x\text{-(Fe}_3\text{O}_4)_{1-x}$ composite films have been described in details elsewhere [3]. Our MR values are defined to be $\{R(H = 0.8 \text{ T}) - R(H = 0)\} / R(H = 0)$. Since the Fe_3O_4 films will undergo a Verwey transition at around 120 K [5], the MR measurements have been carried out at temperatures above 150 K.

The magnetite Fe_3O_4 is ferrimagnetic with Curie point at 858 K. The coercive field (H_c) is found to be 480 Oe for pure Fe_3O_4 film at 300 K and it will be saturated at about 0.8 T. The coercive field H_c of $\text{Ag}_x\text{-(Fe}_3\text{O}_4)_{1-x}$ films has been determined to be monotonically decreasing with increasing x . The polycrystalline magnetite film exhibits a small magnetoresistance effect with a negative MR value of about 1.2% at room temperature. As x increases, the magnitude of MR starts to reduce and then MR value even becomes positive. In the case of $x = 0.02$, a negative MR ratio is found again. An anomalous bump appears in the MR vs. x curve in our $\text{Ag}_x\text{-(Fe}_3\text{O}_4)_{1-x}$ system. From a simple interpolation

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Fig. 1. (a) MR values as function of metal content. Inset, the same graph with smaller x region; (b) The difference ΔH of peak field H_P and coercive field H_C at 300 K as a function of Ag content.

combining the contributions from GMR of Fe_3O_4 and OMR of Ag, the MR value of $\text{Ag}_x\text{-(Fe}_3\text{O}_4)_{1-x}$ system should be almost unchanged with x unless x approaches 1 [4]. Hence, besides GMR in Fe_3O_4 and OMR in Ag, another physical mechanism has to be included to account for the large bump of MR in this system. This anomalous positive MR effect is believed due to spin injection from Fe_3O_4 into Ag granules. The spin accumulation in Ag granules induced from polarized current impedes the spin current so that an increasing resistance with field will be observed.

In order to further verify this reasoning, we have investigated the thermal influence on MR. The results are plotted in Fig. 1(a). It shows that the MR effect is getting considerably larger as the temperature is decreasing. Besides, the positive MR region starts at a lower value of x and extends to a higher x on another end. The reduction of MR at small x can be easily understood from the superparamagnetic theory. From TEM pictures, it has been proved that the size of silver grains d is reduced for smaller x . The net magnetic moment induced from the injected spin current in Ag granules will vanish due to the thermal agitation below the superparamagnetic limit. Therefore, even at $d < \delta_s$, one still expects that the interface spin-coupled resistance, R_s , decreases exponentially as d decreases. The energy barrier of the magnetic system is proportional to its volume, namely d^3 . Thus, larger Ag granules should have the opportunity to block the thermal relaxation of spin accumulation. The appearance of positive MR extending to smaller d at lower temperatures is just an indication of thermal effect, which implies electron–

phonon interaction can also induce spin-flip. On the other hand, the MR value should decay with increasing x as $1/d^3 \exp(-d/\delta_s)$ for larger d [6]. The longer spin diffusion length δ_s at lower temperatures [7] results in a larger x when the positive MR disappears. Combining these two factors, one should expect a wider range of positive MR at lower temperatures.

The MR curve is hysteretic and exhibits a maximum at H_P . It has been found that H_P is also decreasing with x , but has a different slope with H_C . If we plot the difference ΔH of peak field H_P and coercive field H_C as a function of x as shown in Fig. 1(b), a bump exists just as seen in Fig. 1(a). It seems to indicate that the appearance of anomalous MR is associated with a non-zero value of ΔH and H_P and H_C should have different origins. The MR effect in pure Fe_3O_4 arises from misalignment of magnetic moments in adjacent ferromagnetic grains that are exchange-decoupled. Therefore, H_P should coincide with H_C for pure Fe_3O_4 film. However, as Ag is present, the spin injection and accumulation starts to show up causing a deviation of H_P from H_C until this effect disappears.

To summarize, we have observed an anomalous MR in $\text{Ag}_x\text{-(Fe}_3\text{O}_4)_{1-x}$. Although Ag granules contribute rather weak in the magnetization but quite significantly modify the magnetoresistance. The phenomenon can be indeed explained in terms of spin injection and accumulation. And the effect can be observed with a larger Ag concentration regime at lower temperatures.

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